Experimental Study of Energetic Trapped Particle Confinement in Large Helical Device(大型ヘリカル装置における高エネルギー捕捉粒子の閉込めに関する実験的研究)

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Abstract

The confinement of energetic ions is one of the important aspects on confinement schemes of toroidal plasma for controlled nuclear fusion. A tokamak with axis-symmetry confines energetic ions except a few percent ions unconfined under the finite banana width effect. Incomplete confinement due to the ripple effect of the toroidal field coil can be reduced by increasing the number of coils. On the other hand, a heliotron generally has three-dimensional geometry and might suffer from severe energetic ion losses. However, a heliotron has advantage of no current disruption. Therefore, study of energetic ion on Large Helical Device (LHD) is undertaken in the present thesis. Characteristics of the trapped ions in heliotron are different from those in tokamak. Energetic ion orbits in LHD are classified into five orbits judging from trajectories patterns of the drift motions: 1) passing orbit; 2) helically trapped orbit; 3) transition orbit; 4) locally trapped orbit; 5) lost orbit. In this thesis, I call orbits of 2), 3) and 4) as energetic trapped orbit. It has been found that passing ions are well confined in heliotron. Therefore, tangential neutral beam injections (NBI) in LHD are adopted. The confinement of energetic trapped ions produced by ICRF, those produced via pitch angle scatterings from tangential NBI and the confinement of trapped α in α particles produced with isotropic velocity distribution are not still investigated. The study of 180keV protons in LHD with magnetic field strength B of 3T, plasma minor radius a of 1m and plasma volume V of 30m^3 corresponds to simulation study of α particle in a heliotron type reactor with B of 5T, a of 3m and V of 1000m^3.

Energetic trapped ions have to be confined until the plasma is heated fully. It is necessary that low energy trapped ions after giving the energy to the plasma are lost as ash. It is important to investigate to the ratio of confinement time of energetic trapped ions to the slowing down time.

Considering these aspects, experiment used ICRF heating is undertaken. It is possible to produce the energetic trapped ion by ICRF and to couple the resonance particles with specific orbit by using characteristics shapes of ICRF resonance. In this study, by using on-axis and saddle shape resonances, confinement time of helically trapped and transition ions are investigated experimentally. The diagnosis tool used is neutral particle analyzer (NPA) based on natural diamond detector (NDD). The measured tail temperature increases linearly as Stix-temperature increases and then saturation follows indicating the effect of finite confinement time of the energetic ions. In the linear region, the tail readily increases when the line-of-sight looks at the resonance area. The confinement time is obtained from the comparison with the empirical relation based on Stix-theory. The confinement time of helically trapped and transition ions are ~0.31 and ~0.24s, respectively. Analyses of the experimental measurements are consistent with the theoretical calculations including collisional ripple-induced transport.

In heliotron, sever loss of energetic trapped ions has been predicted because of three-dimensional magnetic configuration. Because it is possible to alter the magnetic configuration flexibly by operating current of helical winding and poloidal coils on LHD, it has been proposed to improve confinement of trapped ions by optimizing the magnetic configuration. It is important to prove experimentally the theoretical prediction. In order to understand general improvement by magnetic configuration, tangential NBI system without resonance particles is used. The diagnosis tool used in the present experiment is NDD. Three different configurations having magnetic axis R_{ax} of 3.53, 3.6 and 3.75m on LHD are used. It is predicted theoretically that the configuration at R_{ax} of 3.53m gives the most improved confinement properties to energetic trapped ions. A NDD is installed to measure energetic trapped ions in these configurations. The counter injected neutral beams (NB)s for auxiliary heating produce passing ions and become energetic trapped ions through the slowing down and deflection processes. It is possible to obtain the "integrated" information including a variety of orbits from passing ions to trapped ions. The effect of NB depositions on confinement of energetic ion is also investigated by arranging the time with single and simultaneous NB injections. The measured perpendicular effective temperature and number of the particles are investigated by taking into account of NB depositions. In the single NB injection, the confinement of the energetic ions at R_{ax} of 3.75m shows apparently less performance than other two cases and no significant difference is observed on the confinement at R_{ax} of 3.53 and 3.6m. However, it is found that saturation values of the effective temperature and the energetic particle number at R_{ax} of 3.6m are larger than those at R_{ax} of 3.53m in simultaneous

NB injections. The effect of NB depositions on confinement of ions is not observed. Orbit analyses by the Lorentz orbit code show that the configuration at R_{ax} of 3.6m with the largest plasma volume has the largest confinement region and charge exchange (CX) interactions with neutrals have no difference in the configuration at R_{ax} of 3.53 and 3.6m.

For energetic trapped ions confined until the plasma is heated fully, it is important to investigate the slowing down processes are classical from viewpoint of the confinement control of the energetic trapped ions. It is possible to investigate the processes by using different gas discharges, helium and neon. The diagnosis tool used in the study is NDD. The fast neutral energy spectra produced by ICRF proton minority heating in neon and helium majority plasmas sustained by tangentially injected NBs are investigated. It is observed that there are differences between shape of fast neutral energy spectrum in neon plasma and that in helium one on same discharge with similar plasma parameters. Dominant CX processes in neon and helium plasmas are studied. The energy spectra of energetic trapped ions, protons, are obtained by taking into account of each charge state distribution and responsible CX cross-sections. Tail formations of energetic trapped ions in both plasmas are similar for the same heating regime. The relaxation time of the effective temperatures of the energetic trapped ions and its dependence on the slowing down time have also shown no differences, indicating that the acceleration, deceleration by drags and confinement of energetic trapped ions on LHD are similar in neon and helium plasmas.

In order to investigate the confinement of energetic trapped ions with specific orbit, it is necessary to obtain spatially localized information on energetic trapped ions. For this purpose, pellet charge exchange (PCX) method in combination with NPA and pellet injection is the most probable diagnosis tools. In this study, PCX method by using NDD is developed. It is the first trial of this method in heliotron, while the method has been active in tokamak. The NDD is used as a detection system of compact and easy handling. The application of NDD to PCX is the first time in nuclear fusion experiments. It is possible that the viewing chord is as parallel as possible to pellet injection line by taking advantage of the NDD compactness. The flux of fast neutral reaching the NDD by active CX interactions with the ablation cloud of pellet is estimated quantitatively and the fine adjusting remote slit system with piezo function are developed by Goncharov. The electrical circuit with eight channels of discriminator and latching scalar with very fast 100μs samplings is used in order to obtain the energy spectrum. The initial data together with energy spectrum of ions at local point are obtained. By the Lorentz orbit code, it is found that the observed signals come from helically trapped particles.

Energetic trapped ions escaping from the plasma by some reasons have possibility to hit localized point on the first wall. For the study, lost ion probe (LIP) is one of the most probable tools. In order to investigate the loss processes of energetic ions in LHD, LIP is developed. The LIP using a scintillator could get the successes to detect first signals of the ions. The plasma is sustained by co and counter NBIs. The LIP is inserted by 7cm away from the diverter leg. The image signals detected by the ICCD camera show the lost ions with energy of 150keV and pitch angles of ~75 and ~105 degrees by comparing with the grid results by Monte Carlo calculation. Signals by the photomultipliers (PMT)s appear during NB injection. On the discharge termination by turning off the NBI, signals decaying with finite time constant do not synchronize with sudden increase of H_α signals. Orbit calculations based on the Lorentz orbit code show that the detected energetic ions move outside the last closed flux surface (LCFS). It is found by HFREYA code that the detected ions receive pitch angle scatterings. The detected energetic ions cross the LCFS by some reasons such as collisional ripple-induced loss or CX neutralization loss *etc.* and are re-ionized at outside of LCFS.

The Lorentz orbit code, full-gyro orbit code is modified in order to investigate the ion orbit trajectory in LHD. I succeed in reducing the calculation time by modifying methods of magnetic field calculation and in improving the calculation accuracy by modifying the routines for the kinetic equation.

From these studies, it is concluded as follows. Confinement time of helically trapped and transition particles are ~0.31s and ~0.24s, respectively. The confinement time is comparable to the slowing down time of α particles in a future heliotron reactor. It is considered that loss processes of energetic ions are collisional ripple-induced losses. For improving confinement of energetic trapped ions, optimization of magnetic configuration is effective. Slowing down processes of energetic ions are classical. The PCX method and LIP are developed in LHD, and it are proved that these methods have potentials to get local information and loss processes of energetic ions and to use in large heliotron device with super conducting coils. Finally, it can be said that ICRF which couples to helically trapped ions will be an effective tool for heating in a future heliotron reactor.

This thesis is organized as follows. Introduction is described in chapter 1. Chapter 2 is description of the Lorentz orbit code and energetic ion orbits in LHD. In chapter 3, development of diagnosis tools for the study is referred. Chapter 4 shows measurement and analyses results. Finally, summary and conclusion is given in Chapter 5.

論文審査結果の要旨

核融合炉の炉心となるプラズマの閉じ込め方式としてはトカマク型が最も実用に近いと考えられている．しかしトカマクの定常運転にはプラズマ電流の維持と制御が不可欠であり、それにかわる将来の代替方式としてはヘリカル方式が最も有望と考えられている．しかしヘリカル系は、リップルおよび損失領域の構造がトカマクと異なり，そのためヘリカルリップルや局所ミラー磁場に捕捉された粒子の運動が複雑であり、その結果径方向の輸送を増加させる可能性、および高エネルギーイオンの閉じ込めが不十分という問題がかねてより指摘されてきた．よって高エネルギー捕捉粒子の閉じ込めに関する研究は将来のヘリカル炉心プラズマの展望を明らかにする上でも重要な課題のひとつである。

本論文では、世界最大の超伝導装置である大型ヘリカル装置（LHD）において、高エネルギー捕捉粒子の閉じ込めを粒子軌道を特定して定量的に調べ、閉じ込め性能に関わる因子について調査した．さらにこれらの研究の過程において粒子軌道計算手法と計測手法を開発した．

具体的には、捕捉軌道となる磁場に対して垂直となる粒子を観測するため垂直方向の高速中性粒子スペクトルを NDD(Natural Diamond Detector)を用いて測定した．この時、イオンサイクロトロン共鳴（ICRF）加熱を用いると、主として視線上の共鳴領域で加速された粒子を観測する．よって、共鳴領域を移動することにより種類の異なる捕捉粒子を観測し、それぞれの粒子軌道が閉じ込め性能に及ぼす影響を調べた。その結果、最も閉じ込めの良いヘリカルリップル捕捉粒子の閉じ込め時間は、将来のヘリカル炉で発生するα粒子の減速時間と同程度であることという知見が得られた．また、この飽和性は衝突的リップル輸送模型での予測に近いことから、衝突的リップル輸送が、高エネルギーイオンの閉じ込めを左右する重要な因子であることがわかった。また、捕捉粒子閉じ込めが磁場配位に大きく左右され、理論的な予測どおり磁気面とヘリカルリップル捕捉粒子のドリフト面を一致させることが最適条件であること、粒子の減速過程が古典的な衝突模型の予測通りになっていること等が明らかになった。

これらの成果は、将来の核融合炉の炉心プラズマに重要な知見をもたらしたものであり、これらの研究のために斎田氏が開発した計測手法と粒子軌道計算手法は今後のこの分野に重要な進歩をもたらすと考えられる。

よって，本論文は博士(工学)の学位論文として合格と認める。